A POLISHING PAD FOR A CHEMICAL MECHANICAL PLANARIZATION OR POLISHING (CMP) SYSTEM

FIELD OF THE INVENTION

This invention generally relates to polishing systems for electronic materials. More particularly, this invention relates to polishing pads for chemical mechanical polishing (CMP) systems.

BACKGROUND

Many manufacturers use a chemical mechanical polishing or planarization (CMP) process to produce electronic materials such as semiconductors, integrated circuits, and the like. In a typical CMP process, a wafer is polished to produce an essentially level or smooth (planarized) surface at a microscopic level. The planarized surface assists manufacturers in meeting depth-of-focus and other limitations in lithography processes. The wafer can be an oxide or other dielectric, a metal, a semiconductor, a polymer or combination thereof.

During operation of the CMP process, the surface of the wafer to be polished is positioned against a platen, which has a polishing pad facing the wafer. The wafer and the polishing pad usually rotate in the same direction while a polishing slurry is dispensed between the wafer and the polishing pad. The polishing slurry usually is a colloidal silica or other alkali-based solution for an oxide. The polishing slurry usually is an acid-based solution for a metal.

The surface topography of the wafer is reduced by a combination of mechanical and chemical action of the polishing pad and polishing slurry against the surface of the wafer. Along the surface, the material at the highest positions typically experiences the largest applied pressure and is polished faster than material at lower positions. The difference in polish rates between the highest and lowest positions results in the planarization of the wafer surface.

The polish rate of the CMP process typically is sensitive to the surface of the polishing pad. The polish rate tends to decay from an initial maximum value as the pad surface is damaged by the polishing process. A conditioner device often is used to refresh or maintain the polishing pad surface and thus slow or reverse the decay of the polish rate.

The conditioner usually has a diamond coated or similar surface for removing material from the polishing pad. The quantification and correlation of polishing pad surfaces to polishing performance often is difficult to ascertain. Some approaches use standard surface statistics such as roughness (Ra and Rms), skew, and kurtosis to estimate or predict polishing performance based on pad surface statistics. However, these parameters usually have limited correlation to the polishing performance, especially in oxide polishing. These parameters typically describe the entire pad surface. Some CMP processes, notably oxide polishing processes, are typically influenced primarily by changes in the pad-wafer contact area or the near surface region of the polishing pad. In these cases, statistics describing the entire surface of the pad have limited utility. Other approaches correlate the average asperity or roughness of the near surface region to the polishing performance.

BRIEF SUMMARY

This invention provides a chemical mechanical planarization or polishing (CMP) system having a polishing pad with a polish rate responsive to the pad contact area and the mechanical behavior of the polishing pad.

In one aspect, a polishing pad for a CMP system has a surface characterized by a polish rate. The polish rate is responsive to a pad contact area and pad contact dynamics. The pad contact area is characterized by a predetermined statistical distribution of a pad surface height. The pad contact dynamics are characterized by the mechanical behavior of the polishing pad.

In another aspect, a polishing pad for a (CMP) system has a surface characterized by a polish rate. The polish rate is responsive to a statistical distribution of a pad surface height and the mechanical behavior of the polishing pad. The statistical distribution includes a first statistical distribution and a second statistical distribution. The first statistical distribution represents a bulk component of the surface. The second statistical distribution represents a near surface component of the surface. The mechanical behavior of the polishing pad may be described by a full visco-elastic model, or may be approximated as an elastic spring.

In a further aspect, a CMP system has a polishing pad, a platen, a wafer, a holder, and a slurry. The polish pad is disposed on the platen. The wafer is mounted in the

holder. The slurry is disposed between the polish pad and the wafer. The holder is operable to press the wafer against a surface of the polishing pad. The pad is characterized by a preferred statistical distribution of a pad surface height and the mechanical behavior of the polishing pad. The polishing pad has a polish rate responsive to the pad surface height distribution and the mechanical behavior of the polishing pad.

Other systems, methods, features, and advantages of the invention will be or will become apparent to one skilled in the art upon examination of the following figures and detailed description. All such additional systems, methods, features, and advantages are intended to be included within this description, within the scope of the invention, and protected by the accompanying claims.

BRIEF DESCRIPTION OF THE FIGURES

The invention will be better understood with reference to the following figures and detailed description. The components in the figures are not necessarily to scale, emphasis being placed upon illustrating the principles of the invention. Moreover, like reference numerals in the figures designate corresponding parts throughout the different views.

FIG. 1 illustrates a CMP system according to an embodiment;

FIG. 2 illustrates a top view of the polishing pad in the CMP system of FIG. 1 according to one embodiment;

FIGs. 3A and 3B are plots in accordance with the invention illustrating two-dimensional pad surfaces and corresponding pad height histograms of the polishing pad in FIG. 2; in which, FIG. 3A illustrates the polishing pad after a break-in period, and FIG. 3B illustrates a polishing pad after polishing with no conditioning;

FIG. 4 is a plot illustrating a fitting procedure for analyzing the pad height histogram data of a polishing pad in accordance with the invention;

FIG. 5 is a plot illustrating a pad height histrogram and a corresponding cumulative pad volume of a polishing pad in accordance with the invention;

FIGs. 6A, 6B, and 6C are plots illustrating pad surface parameters in accordance with the invention having a statistical correlation with the polish rate at about a 100% confidence level; in which, FIG. 6A illustrates the correlation of the reciprocal of the contact area with the polish rate; FIG. 6B illustrates the correlation of the contact area with

the polish rate; and FIG. 6C illustrates the correlation of the area fraction of the second peak with the polish rate;

FIG. 7A is a plot in accordance with the invention illustrating a correlation according to the invention between the predicted contact area and the polish rate of a polishing pad in a CMP system for different polishing slurries with the same conditioning disc;

FIG. 7B is a plot in accordance with the invention illustrating a correlation according to the invention between the predicted contact area and the polish rate of a polishing pad in a CMP system for the same polishing slurry and different conditioning discs;

FIG. 7C is a plot in accordance with the invention illustrating polishing rate as s function of predicted pad contact area; and

FIGs. 8A and 8B are plots in accordance with the invention illustrating a reduced polish rate in an oxide polishing process as a function of a frictional loading factor FIG. 8A and the Sommerfeld number FIG. 8B.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

FIG. 1 illustrates a CMP system 100 according to an embodiment of the invention. The CMP system 100 has a platen 102, a polishing pad 104, a wafer 106, a holder 108, a polishing slurry 110, and a pad conditioner 112. The platen 102 holds and provides structural support for the polishing pad 104. The holder 108 carries and presses the wafer 106 against the polishing pad 104. During operation, the platen 102 and holder 108 rotate. The platen 102 rotates in the range of about 0 rpm through about 150 rpm. The holder 108 also rotates in the range of about 0 rpm through about 150 rpm. The platen 102 and holder 108 can rotate at other speeds. The rotation speeds of the platen and holder need not be equal. The rotating wafer 106 presses against the rotating polishing pad 104 while the polishing slurry 110 is dispensed between the wafer 106 and the polishing pad 104. The applied pressure between the wafer 106 and the polishing pad 104 is in the range of about 0-15 psi. Other pressures can be used. The CMP system 100 can have other configurations and arrangements including those with fewer and additional components and those with other or different process parameters.

The polishing pad 104 is a rigid, microporous polyurethane-based pad such as the Rodel® IC1000 CMP Pad from Rodel, Inc. of Phoenix, Arizona. To fabricate the polishing pad, any prepolymer chemistry can be used in accordance with the present invention, including polymer systems other than urethanes, provided the final product exhibits the following properties: a density of greater than about 0.5 g/cm^3, more preferably greater than about 0.7 g/cm^3 and yet more preferably greater than about 0.9 g/cm^3; a tensile modulus of about 0.02 to about 5 GigaPascals; hardness of about 25 to about 80 Shore D; a yield stress of about 300 to about 6000 psi; a tensile strength of about 500 to about 15,000 psi, and an elongation to break up to about 500%. These properties are possible for a number of materials useful in extrusion and similar-type processes, such as: polycarbonate, polysulphone, nylon, ethylene copolymers, polyethers, polyesters, polyether-polyester copolymers, acrylic polymers, polymethyl methacrylate, polyvinyl chloride, polycarbonate, polyethylene copolymers, polyethylene imine, polyurethanes, polyether imide, polyketones, and the like, including photochemical reactive derivatives thereof.

In one embodiment, the pad matrix is derived from at least one of: an acrylated urethane; an acrylated epoxy; an ethylenically unsaturated organic compound having a carboxyl, benzyl, or amide functionality; an aminoplast derivative having a pendant unsaturated carbonyl group; an isocyanurate derivative having at least one pendant acrylate group; a vinyl ether, a urethane; a polyacrylamide; an ethylene/ester copolymer or an acid derivative thereof; a polyvinyl alcohol; a polymethyl methacrylate; a polysulfone; an polyamide; a polycarbonate; a polyvinyl chloride; an epoxy; a copolymer of the above; or a combination thereof. Preferred pad materials comprise urethane, carbonate, amide, sulfone, vinyl chloride, acrylate, methacrylate, vinyl alcohol, ester or acrylamide moieties. The pad material can be porous or non-porous. In one embodiment, the matrix is non-porous; in another embodiment, the matrix is non-porous and free of fiber reinforcement. The pad material may also contain abrasives. The polishing pad 104 can include other materials and can have other configurations including those with other or different process parameters. Polishing pads having the above material characteristics are also described in commonly-assigned, U.S. Patent No. 6,287,185, which is incorporated by reference herein.

The pad conditioner 112 presses against and sweeps radially across the polishing pad 104 during operation of the CMP system 100. The pad conditioner 112 has a diamond-covered conditioning surface such as the DiaGrid® brand Pad Conditioner available from Rodel, Inc. of Phoenix, Arizona. The conditioning surface regenerates or refreshes the top surface by removing pad material to create more asperities in the polishing pad 104. The asperities created by the pad conditioner 112 can have different shapes such as spherical, non-spherical, arbitrary, and a combination thereof. The pad conditioner 112 has a density of diamonds on the conditioning surface in the range of about $1/mm^2$ through about $100/mm^2$. The nominal size of individual diamonds on the conditioner surface is in the range of about 20 micrometers (μm) through about 500 μm. The diamond crystal type can be varied over a range including, angular, blocky, mosaic and cubo-octahedral shapes. The pad conditioner 112 has a pad removal rate in the range of about 0 μm /hour through about 500 μm/hour of conditioning time. The conditioner has an applied load in the range of about 0 lbs through about 50 lbs on the polishing pad 104. Other pad conditioners can be used including those with different or other process parameters.

The wafer 106 includes an electronic material such as a semiconductor, an integrated circuit, and the like. In one aspect, the wafer 106 includes an oxide. In another aspect, the wafer 106 includes a metal or alloy. In a further aspect, the wafer 106 includes an oxide with a metal layer such as silicon dioxide with a tungsten layer. In a further aspect the wafer 106 includes a oxide or low-k dielectric material with a copper layer. The wafer 106 can include one or more of Si, SiO_2, Cu, Ta, TaN, W, GaAs, TiN, Ti, Si_3N_4, and the like. The wafer may be composed other materials than those listed here.

The polishing slurry 110 can be a colloidal silica or other alkali-based solution such as Rodel® ILD1300, KLEBOSOL®, or a combination thereof. The Rodel® ILD1300 slurry can be obtained through Rodel, Inc. of Phoenix Arizona. The KLEBOSOL® slurry can be obtained through Clariant Corporation of Charlotte, North Carolina. The polishing slurry 110 can include other etchant solutions and combinations including acid-based solutions. Alternatively, the polishing solution can be a reactive liquid composition that does not contain an abrasive component.

The surface of the wafer 106 is planarized or polished by the mechanical friction and chemical etching of the polishing pad 104 and the polishing slurry 110. The polish

rate of the polishing pad 104 is responsive to the pad contact area and the contact dynamics of the polishing pad 104 with the wafer 106. As described below, the pad surface area can be characterized by a statistical representation of the pad surface. The pad contact dynamics can be ascertained from pad surface height statistics and the mechanical behavior of the polishing pad 104, the properties of the polishing slurry, and the process conditions. The pad surface data is analyzed by fitting a pad height histogram with one or more Gaussian or modified Gaussian components. The pad height histogram represents the distribution of asperities on the pad surface. The subtle differences or localized differences in the pad surface can be assessed quantitatively. The components of the fit can be described with a small set of parameters, which correlate with polish performance. The mechanical behavior of the pad can be described by modeling the volumetric displacement of the pad as an elastic spring. Other elastic or visco-elastic models for the pad mechanical behavior can be used. The pad contact area and the contact dynamics can be used to obtain or determine an optimal polish rate for the polishing pad 104. In one aspect, the optimal polish rate corresponds to rate-saturated conditioning, where the regeneration of the pad surface by the conditioner is about equal to the deformation of pad asperities by the wafer. The optimal polish rate can correspond to other contact dynamics and contact area parameters between the polishing pad 104 and the wafer 106.

FIG. 2 represents a top view of the polishing pad 104 in the CMP system 100 according to one embodiment. The polishing pad 104 has a top surface 120 including a non-contact portion 122 and a contact track or path 124. The wafer 106 does not contact the polishing pad 104 on the non-contact portion 122 during operation of the CMP system 100. The wafer 106 contacts the polishing pad 104 at a pad-wafer contact area 126, which follows the contact track or path 124 during operation of the CMP system 100. The top surface 120 has a surface texture or morphology. The top surface 120 can have other configurations and arrangements including other or different non-contact portions and contact tracks or paths.

The surface texture or morphology of the top surface 120 is characterized by asperities, which are the variations in the pad height along the top surface. The asperities are initially present in the polishing pad 104 and can be created by the conditioner 112 prior to or during operation of the CMP system 100. The height of each asperity can be

measured in relation to a zero height position. The zero height position can be a geometric average of all the asperities, a single asperity height such as the highest or lowest asperity, or some other predetermined level. The distribution of asperities is represented statistically by a pad height histogram. The asperities can have one or more shapes including spherical, non-spherical, and arbitrary shapes.

The pad surface texture is analyzed to determine the pad surface contact area and other data associated with the pad contact dynamics. The pad surface texture can be analyzed initially to provide set-point or standard data for a given type of polishing pad 104. These set-point data would be available to determine the optimal polish rate of the polishing pad 104 under various operating conditions of the CMP system 100. The pad surface texture also can be analyzed during operation of the CMP system 100 to establish or update the data.

The pad surface texture is analyzed using a vertically scanning interference microscope such as the WYKO NT3300 from Veeco Instruments, Inc. of Woodbury, New York. Other interference microscopes or other surface texture measurement devices can be used. The pad surface texture is characterized using various statistics such as standard roughness parameters and a height histogram peak fitting procedure outlined below. In one aspect, the pad surface feature is measured using multiple azimuthal or radial locations on the pad for a given time interval. In addition to standard roughness parameters, pad surface texture statistics are analyzed using the peak fitting procedure.

FIGs. 3A and 3B represent two-dimensional pad surfaces and corresponding pad height histograms of the polishing pad in FIG. 2. The two-dimensional pad surfaces are taken from line scans of the three-dimensional pad surface data from the contact track or path 124 of the polishing pad 104. FIG. 3A represents a polishing pad after a break-in period. FIG. 3B represents a polishing pad after about 31 minutes of polishing with no conditioning. The pad height histograms have been rotated 90° to correspond to the pad-height axis of the pad cross-sections. FIG.s 3A and 3B illustrate a qualitative picture of the physical implications of the height histogram data. In FIG. 3A, the post break-in surface is not deformed by pad-wafer contact and exhibits a smooth, tailed Gaussian distribution of pad surface height. In FIG. 3B, prolonged pad-wafer contact, especially in the absence of conditioning, results in a pad with a flattened surface. In the pad-height

data, this corresponds to the emergence of a secondary mode in the histogram near the pad surface.

FIG. 4 illustrates a fitting procedure for analyzing the pad height histogram data of a polishing pad. The histogram shows point frequency as a function of pad-height. The designation of zero height is based on the geometric average of the data set. The height distribution has been fitted with a two-component system consisting of two distinct Gaussian or exponentially modified Gaussian contributions. The asperities not in contact with the wafer represent a primary (bulk) component of the pad surface and are described by an exponentially modified Gaussian (EMG) distribution. The "as-conditioned" surface of the polishing pad can be described by a similar distribution as the bulk component. An EMG distribution can be thought of as a Gaussian distribution with a superimposed exponential "tail". The asperities in contact or near to contact with the wafer represent a secondary (near surface) component of the pad surface and are described by either a Gaussian or EMG distribution. This combination of Gaussian and EMG distributions provides a system that captures a majority of the distribution behavior of contact and non-contact areas for a wide range of data sets.

A Gaussian and EMG combination is useful in situations where the secondary component can not exhibit a distinct maximum. In these cases, a secondary component represented as an EMG can exhibit severe tailing by attempting to minimize the overall error of the fit whereas a secondary component represent as Gaussian will not. In a CMP system using an IC1000 polishing pad, a ILD1300 polishing slurry, and a cubic-octahedral conditioner, a distinct secondary maximum is observed in the histogram and therefore the tail of the distribution can be adjusted on both the primary and secondary components to obtain a satisfactory fit. The tendency of the secondary component to exhibit a severe tail can be statistically limited by the slope of the secondary maximum. Other combinations of statistical distributions, specifically Pearson distributions or modified Gaussian distributions with additional adjustable parameters, can be used and, in some cases, can be more effective at capturing the pad height histogram distribution. However, as the number of adjustable parameters increases, the statistical ability to attach physical significance to those parameters decreases.

The Gaussian distribution can be described mathematically according to

Equation 1 as follows:

$$y = a_0 \exp\left[-\tfrac{1}{2}\left(\frac{x - a_1}{a_2} \right)^2 \right] \quad , \qquad (1)$$

where the constants a_0, a_1 and a_2 refer to the amplitude, center, and width of the standard deviation.

The EMG distribution can be described mathematically according to Equation 2 as follows:

$$y = \frac{a_0}{2a_3} \exp\left(\frac{a_2^2}{2a_3^2} + \frac{a_1 - x}{a_3} \right)\left[erf\left(\frac{x - a_1}{\sqrt{2}\, a_2} - \frac{a_2}{\sqrt{2}\, a_3} \right) + \frac{a_3}{|a_3|} \right] \quad , \qquad (2)$$

where a1 and a2 represent the center and width of de-convolved Gaussian contribution to the overall peak, which is defined as Gauss(a_0,a_1,a_2) $\otimes$ Exp(a_3), and where a_3 is the time constant of the exponential contribution.

Based on the fitting results, the height histogram data can be described with a handful of parameters as previously discussed. The peak fit results can be obtained using non-linear curve fitting software such as the PeakFit® software package from SPSS Science in Chicago, Illinois. Other curve fitting software and procedures can be used.

The contact dynamics are responsive to the mechanical behavior of the polishing pad 104. The pad-wafer contact area can be estimated using an elastic model for the mechanical behavior of the polishing pad 104. Hooke's Law provides the elastic model according to Equation 3 as follows:

$$\sigma = k \frac{\Delta l}{l} \quad , \qquad (3)$$

where σ is the stress, k is an effective spring constant of the polishing pad 104, l is the length or thickness of the polishing pad 104, and Δl is the change in length or deflection of the polishing pad 104.

The effective spring constant of an IC1000 pad is about 4.5 x 10^8 Pa. Using Hooke's Law, a 62 kPa stress on the pad yields a pad deflection of about 0.135 µm. A

wafer pressure of about 9 psi can provide the 62 kPa stress on the pad. Over a 1800 x 2400 μm area, which is a scan area for the pad analysis, the pad deflection would result in a displaced pad volume of about 5.8 x 10^5 μm^3. Other scan areas can be analyzed. While Hooke's Law is used as the elastic pad model, any other elastic or visco-elastic model of the pad mechanical behavior can be used. In one aspect, the pad model incorporates a more accurate description of the pad visco-elastic behavior. In another aspect, the pad model incorporates x-y pad "asperity" distributions as well as the z-distributions already considered.

Numerical integration of the pad height histogram yields a cumulative pad displaced volume as a function of pad height. The numerical integration to determine the displaced pad volume can be performed according to Equation 4, as follows:

$$V = \sum_{i=1}^{b} \left[h_i A_p \sum_{i=1}^{b} n_i \right] \quad , \qquad (4)$$

where the pad height histogram is divided into "b" bins with n_i points or pixels in each bin, where A_p is the area associated with each discrete point (or pixel) in the scan, and where h_i is the z-height of the bin.

The bins are numbered consecutively starting with the highest point in the scan and moving down through the pad. Comparison of the predicted displaced volume with the calculated pad volume yields an estimate of the depth of wafer penetration into the pad and also the contact area between the wafer and the pad. This procedure represents the numerical equivalent of pressing the wafer 106 into the polishing pad 104 and quantifying the area of pad in contact with the wafer.

FIG. 5 illustrates a pad height histogram and a corresponding cumulative pad volume of a polishing pad. The point at which the predicted displaced volume is about equal to the cumulative pad volume is shown. The pad has a predicted contact area of about 10.4 %, which corresponds to a pad height of 7.3 μm.

FIGs. 6A, 6B, and 6C illustrate pad surface parameters having a statistical correlation with the polish rate at about a 100% confidence level. FIG. 6A illustrates the correlation of the reciprocal of the contact area with the polish rate. FIG. 6B illustrates the correlation of the contact area with the polish rate. FIG. 6C illustrates the correlation of

the area fraction of the second peak with the polish rate. The correlation of these pad surface parameters, especially the reciprocal contact area which (given a constant applied force to the wafer) represents a mean asperity pressure, indicates the asperity contact mechanism underlying the cause of polish rate decay. In one aspect, the pad surface parameters are from a CMP system using ILD1300 slurry and an IC1000 pad. Other CMP systems can provide similar confidence levels for similar parameters. Other pad surface parameters also can have a strong correlation with the polish rate. Some pad surface parameters can not have a strong correlation with the polish rate. In one aspect, none of the standard roughness parameters are strongly correlated with the polish rate.

FIG. 7A illustrates a correlation between the predicted contact area and the polish rate of a polishing pad in a CMP system. The data show the results of several polishing slurries when used with an IC1000 polishing pad. The data in FIG. 7A was generated by first achieving a steady state polish rate with pad conditioning, and then suspending pad conditioning and tracking the resulting evolution of both the polish rate and the corresponding pad surface state. Generally, predicted pad contact area always increases as a function of time without conditioning from a minimum steady state value. A single and consistent conditioner design was used to generate the data in FIG. 7A.

As indicated in FIG. 7A, polishing slurries ILD1300, and Rodel® ILD1300 J9 show an increase in the polish rate as the contact area decreases. Conversely, polishing slurries Klebosol and a mixture of Klebosol with ILD1300 show an increase in the polish rate as the contact area increases up to about 6% contact area, a local maximum in rate at around 6 % contact area, and a decrease in rate above 6%.

FIG. 7B shows the results of multiple conditioners of varying design on the correlation between predicted contact area and polish rate when using ILD1300 slurry. All of the data in FIG. 7B were generated after a steady state polish rate was achieved with conditioning, such that each data point in FIG. 7B represents a steady state value at an equivalent process condition with only the conditioner design being varied. A wide range of diamond crystal spacing (from $1/mm^2$ to $3.3/mm^2$), diamond crystal size (from 150-210 μm) as well as diamond crystal types (angular, blocky, mosaic and cubo-octahedral) were evaluated in these experiments. The conditioners exhibiting more aggressiveness, as measured by the amount of pad material removed per unit time, result in pad surfaces with

lower percent contact area. Accordingly, the design of the conditioner has a dramatic effect on the percent of pad area in contact with the wafer and also the polish rate.

In a preferred embodiment of the invention, the pad conditioner can have diamond crystal sizes ranging form about 20 microns to about 500 microns. Also, the spatial density of diamond crystals can vary from about 1 to about 100 per square millimeter. Further, the pad conditioner is configured such that the removal rate of pad material ranges from about 0 microns per hour to about 200 microns per hour.

FIG. 7C illustrates polish rate versus contact area for multiple conditioners of varying design on the correlation between predicted contact area and polish rate when using ILD1300 slurry and a Rodel® OXP4000 polishing pad. The data in FIG. 7C was generated by first achieving a steady state polish rate with pad conditioning, and then suspending pad conditioning and tracking the resulting evolution of both the polish rate and the corresponding pad surface state. As in the case of the data in FIG. 7A and 7B, the data in FIG. 7C exhibit a maximum in polish rate. In this case, the maximum is present at around 3.5 % pad contact area. Since the process conditions in this run were identical to those used in FIG 7A and 7B, the primary difference is the mechanical properties of IC1000 pad versus OXP4000 pad. This example serves to illustrate the potential variations in polish rate maxima as a function of pad mechanical properties.

In a one embodiment, the polish rate has a maximum within a range of about 0 % to about 15% pad contact area. In another embodiment, the polish rate has a maximum within a range of about 3 % to about 8% pad contact area. In yet another embodiment, the polish rate has a maximum at about 6% pad contact area. In a further embodiment, the polish rate has a maximum at about 3.5% pad contact area. . The optimal pad-wafer surface contact area varies depending on process conditions, such as pad properties, slurry, wafer type, platen and carrier speeds, and the like. The optimal pad-wafer surface contact area also varies depending on the pad physical properties. Other methods of calculating pad contact area may yield a different estimate for the same process conditions and pad surface statistics.

Two competing processes determine the pad surface texture. The pad conditioner 112 operates to maintain a nearly normal distribution of pad heights through the constant removal of pad material and regeneration of the pad surface. The pressure of the wafer against the pad surface results in plastic deformation of the near surface pad

asperities and a blunted pad surface height distribution. The amount of pad surface in contact with the wafer is highly dependent on the pad height distribution, which can be visualized by comparing extreme cases of a pad asperity such a square cross-section with a conical cross-section. For equivalent small volume displacements, the square asperity exhibits a higher contact area than the conical asperity.

By analogy and supported by the elastic model applied to the pad height distribution data, the as-conditioned pad surface also exhibits a lower predicted pad contact area. The pad-wafer contact shifts the pad height distribution towards more pad area in contact with the wafer. The slurry type can have a large effect on this interaction, with colloidal slurries exhibiting minimal pad distortion and fumed silica slurries exhibiting more pad surface distortion. While the pad surface area in contact with the wafer is determined by the slurry type, the polish rate appears to be independent of slurry type and determined primarily by pad contact area. There is an optimal amount of pad surface contact that corresponds to a maximum polish rate for the system. Below this optimal contact area, polish rate drops and tends towards zero rate for zero area in contact. Above this optimal level, the polish rate drops with increasing contact area. In a low contact area regime, the polish rate can be limited by the fact that a limited number of point contacts exist such that sufficient averaging cannot take place over the entire wafer surface. Above the optimal value, the polish rate can be limited by the dynamics of the pad wafer contact such as a reduction in mean contact pressure or some other effect. In one aspect, the optimal polish rate or range can be characterized as "rate-saturated conditioning". When the pad contact area is less than the optimal, the pad contact area can be characterized as "over-saturated" conditioning. When the pad contact area is more than the optimal, the pad contact area can be characterized as "under-saturated" conditioning.

A dominant contributor to polish rate decay is conditioner wear. The conditioner wear could drive the process from a conditioning dominated state to more of a wafer dominated state with a subsequent loss in removal rate as the operating point shifts towards a higher pad contact area. The initial conditioner dominated process state is a function of the slurry type, in that the slurry type has a large influence on the degree to which the wafer-pad interaction causes pad asperity "clipping". The steady-state contact area can vary.

In one aspect, an *in situ* process with Klebosol 1501-50 has a steady-state contact area of about 4%. In another aspect, an *ex situ* Klebosol process has a steady-state contact area of about 7%. In a further aspect, an *in situ* process using ILD1300 exhibits a steady state contact area of around 10%. In yet another aspect, fumed silica slurries are not driven to a rate-saturated state, even with 100% *in situ* conditioning. In yet a further aspect, with a more aggressive conditioning process or a more aggressive conditioner design, the conditioner contribution can increase and the operating point can be driven to a rate saturated state. In one more aspect, a conditioning controlled, rate-maximized process could be designed if the surface morphology that corresponds to an optimal polish rate could be determined. A conditioner could potentially be designed to result in a desired amount of asperity "clipping" to yield the optimal polish rate. When driven to a conditioning saturated operating point, a high rate could be maintained, independent of the slurry type. Pad-aggressive slurries (such as fumed silica) would have more aggressive conditioning to maintain the optimal surface.

FIGs. 8A and 8B illustrate the relationship between the polish rate (defined as the measured polish rate divided by the product of wafer applied pressure and relative velocity between the wafer and pad) and a frictional loading factor ($\mu V/P_c$), FIG. 8A, and the Sommerfeld number ($\mu V A_c/P\sigma$), FIG. 8B, where P is the applied pressure to the wafer, V is the relative velocity between the wafer and pad, A_c is the area contact fraction between the wafer and pad, such that contact pressure P_c equals P/A_c, μ is the slurry viscosity, and σ is a characteristic length scale taken to be equivalent to the average pad roughness, R_a.

Those skilled in the art will recognize the Sommerfeld number as the ratio of viscous to pressure forces. As illustrated in FIG. 8B, boundary lubrication, where the behavior at the pad wafer interface would be dominated by contact mechanics, occurs when S_o is less than about 1. Alternatively, mixed lubrication, where hydrodynamic effects become significant, occurs in the range where S_o is greater than about 1 and less than about 3. In accordance with the invention, the Sommerfeld number can ranges from about 0 to about 3.

In accordance with the invention, evaluation of frictional loading factors and pressure forces enables the design of a polishing system to exploit the relative effects of a contact dominated or a hydrodynamically dominated system. Since the polish behavior resulting from the frictional forces at the pad-wafer interface is significantly different in

the opposing regimes, analysis and exploitation of this behavior provides a pad-slurry-process system with improved polishing characteristics.

Various embodiments of the invention have been described and illustrated. However, the description and illustrations are by way of example only. Other embodiments and implementations are possible within the scope of this invention and will be apparent to those of ordinary skill in the art. Therefore, the invention is not limited to the specific details, representative embodiments, and illustrated examples in this description. Accordingly, the invention is not to be restricted except in light as necessitated by the accompanying claims and their equivalents.